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## Article

# Testing the Environmental Seismic Intensity Scale on Data Derived from the Earthquakes of 1626, 1759, 1819, and 1904 in Fennoscandia, Northern Europe

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**Abstract:** Earthquake environmental effects (EEEs) were compiled for the earthquakes of 1626, 1759, 1819, and 1904 in the Fennoscandian Peninsula, northern Europe. The principal source of information was the contemporary newspaper press. Macroseismic questionnaires collected in 1759 and 1904 were also consulted. We prepared maps showing newly discovered EEEs together with previously known EEEs and analyzed their spatial distribution. We assigned intensities based on the 2007 Environmental Seismic Intensity (ESI) scale to 27 selected localities and compared them to intensities assigned based on the 1998 European Macroseismic Scale. While the overall agreement between the scales is good, intensities may remain uncertain due to the sparsity of written documentation. The collected data sets are most probably incomplete but still show that EEEs are not unprecedented cases in the target region. The findings include landslides and rockfalls as well as cascade effects with a risk potential and widespread water movements up to long distances. The winter earthquake of 1759 cracked ice over a large area. This investigation demonstrates that the ESI scale also has practical importance for regions with infrequent EEEs.

**Keywords:** historical seismology; earthquake environmental effect; environmental seismic intensity scale; macroseismic intensity; newspaper; Kattegat earthquake of 1759; Lurøy; Norway; earthquake of 1819; Oslofjord earthquake of 1904



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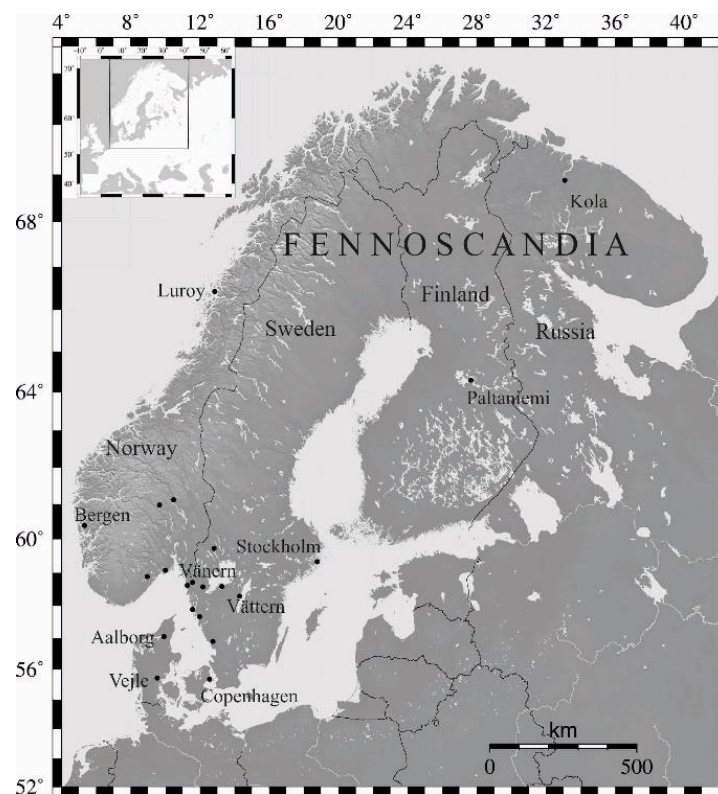
## 1. Introduction

Macroseismology is defined as the study of any effects of earthquakes that are observable without instruments, such as ground shaking felt by people, landslides, fissures, and knocked-down chimneys [1]. Seismologists and civil engineers may investigate such effects in the immediate aftermath of an earthquake. The collected information is empirical, indisputable evidence, which should not be bypassed in future earthquake risk scenarios.

Historical macroseismology investigates various written documentary materials that testify to the effects of earthquakes in the past. Photos and eyewitness observations depicted in drawings and paintings may also be utilized. Cooperation between historians and geoscientists has contributed to the great strides made in the field (e.g., [2]). Intensity assignment becomes more complicated than in the case of recent earthquakes, because older data have passed through the filters of transmission and reception [3]. The original level and detail of documentation, possible distortions of the earthquake's true effects, and the survival of documents to the present day constitute the transmission filters. Retrieval of existent documentation and seismologists' ability to interpret old texts comprise the reception filters.

In this investigation, the Environmental Seismic Intensity Scale ESI-07 (e.g., [4–6]) is tested on historical earthquake data from the Fennoscandian Peninsula, in northern Europe (Figure 1). It is an intraplate domain where moderate-to-large earthquakes seldom occur

and short-term (instrumental) data must be extended back in time to improve knowledge of earthquake consequences. Systematic collection of earthquake environmental effects (EEEs) has the potential to complement the view of earthquake consequences in the target region over a period of three to four centuries.



**Figure 1.** The target region.

Macroseismic questionnaires were first introduced in Finland, Norway, and Sweden in the 1880s [7–10]. Intensity has been assigned to different scales over the course of time, including the Rossi–Forel, Medvedev–Sponheuer–Kárník (MSK-64), and Modified Mercalli Intensity; presently, the European Macroseismic Scale EMS-98 [11] is used. Most data collected using questionnaires record transient earthquake effect on people and objects, and the corresponding intensities extend over a narrow range at the lower end of the scales.

The wooden houses typical of Fennoscandia differ from dwellings in central and southern Europe, where several of the prevalent macroseismic scales were developed since the late 1800s. The wooden houses were resilient and often sturdy enough to bear snow loads and heavy winds; however, their quality depended on the availability of timber [12]. The grade of possible damage during ground shaking must be assessed mainly from the unreinforced masonry parts of structures, such as foundations, stoves, and chimneystacks. Damage to buildings has been reported only rarely (e.g., [13]).

Submarine slopes and seismic sea waves in the North Sea as well as earthquake effects on slopes in Norway have previously been reviewed [12]. Likewise, notifications of earthquake-triggered landslides in Norway have been collected [14], and the ESI scale has previously been used in paleoseismology in Fennoscandia [15,16].

We thus opted to search for hitherto disregarded EEEs for the important earthquakes of 1626, 1759, 1819, and 1904, and analyze their geographical distribution (Section 2). The collected questionnaires and contemporary newspaper reports are also promising sources for finding descriptions of EEEs. We assigned intensities on the ESI-07 scale to 27 selected localities and compared them to EMS-98 intensities (Section 3). The findings are then discussed (Section 4).

## 2. Compilation of EEE Data

In this section, EEEs are compiled and analyzed for the four earthquakes.

### 2.1. Earthquake Activity in North-Eastern Fennoscandia in the Spring of 1626

The preinstrumental seismicity record in northern Fennoscandia is very sporadic until the mid-1700s, and only fragmentary macroseismic documents attest to the oldest earthquakes. An example is the seismicity from June 1626: the origin time(s) and magnitude(s) of the seismic activity cannot be resolved unambiguously based on existing documentation in Finland and north-western Russia. In the absence of ample data, the scenarios for two separate earthquakes or a single earthquake felt in both territories are considered equally likely [17].

A slope failure is described in one contemporary chronicle. It was inferred to have occurred in Paltaniemi, by Lake Oulujärvi, northern Finland [17]. The banks of Lake Oulujärvi are notoriously unstable (Figure 2) and were almost certainly affected by the seismic activity in 1626. No information on weather conditions at the time is available, but it is possible that the lake's banks were saturated by melting snow.



**Figure 2.** Banks of Lake Oulujärvi, northern Finland, in 1910 (unidentified photographer M.N.H.; photo: Museum of Kainuu, northern Finland). Today the banks are covered with abundant vegetation.

### 2.2. The Kattegat Earthquake of 1759

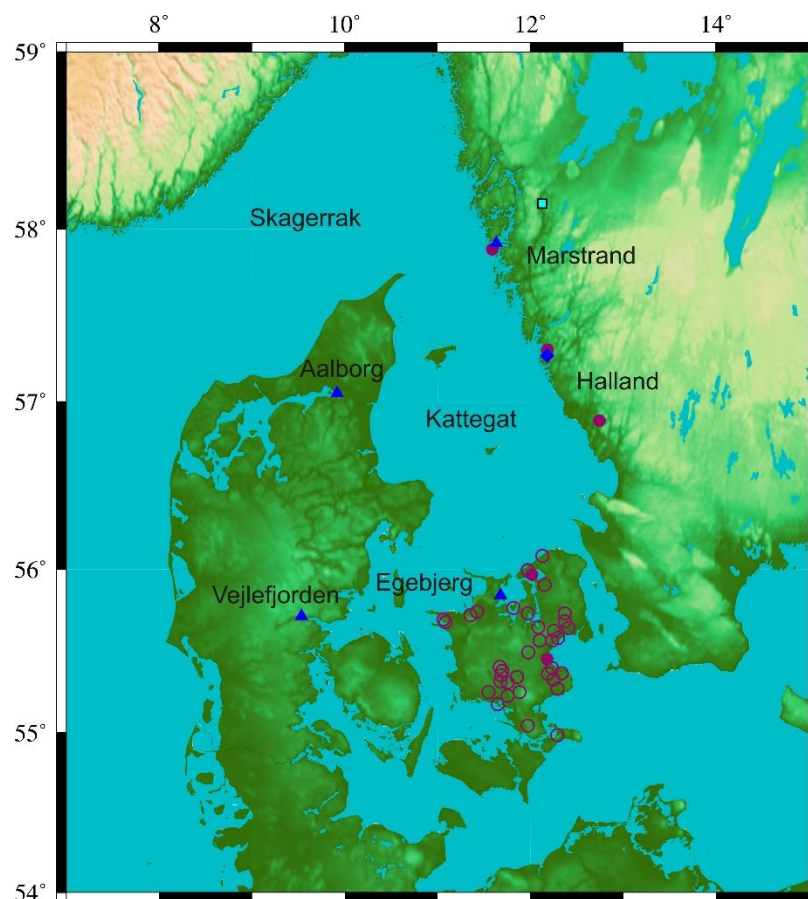
A major historical earthquake occurred in the Strait of Kattegat on 21 December 1759 (local time between midnight and 1:00 a.m. on 22 December). It has been located at latitude  $58.20^{\circ}$  N and longitude  $10.60^{\circ}$  E, with an estimated error between 30 and 69 km [12]. Estimates assign a surface-wave magnitude of  $M_S 5.4$ – $5.6$  for the earthquake [18].

We searched for notifications of EEEs in the contemporary documentation. The 1759 Kattegat earthquake was the first major event in the target region to attract ample coverage in the press [10]. Important newspapers were published in the cities of Copenhagen and Gothenburg, not far from the epicenter. Abundant additional information is available for Zealand, the largest island in Denmark proper, where the bishop of Zealand Ludvig Johansen Harboe (1709–1783) collected observations from vicars in his diocese using a questionnaire format. Circulars represented an established practice for collecting information on different subjects within the diocese. After the earthquake, a circular composed of seven questions was designed, with the last question reading as follows: “Whether any phenomena with lightning, unusual roaring of the sea etc. either preceded or followed the earthquake.” In seismological terms, this was an early macroseismic survey including an EEE standpoint.

We investigated the circulars returned to Bishop Harboe from the parishes in the Zealand diocese, later published in a book [19]. The survey recorded many negative



reports on water movements, meaning that the water was reportedly calm (Figure 3). A newspaper account stated that no water movements were observed in Copenhagen, but they did occur in the surrounding countryside [20]. This finding corresponds with two circulars referring to Køge, south of Copenhagen, where a fisherman noticed unusual water movements [19] (pp. 130, 132). The tremor was also strongly felt in the water around Frederiksværk [19] (p. 91).



**Figure 3.** Earthquake environmental effects related to the Kattegat earthquake on 21 December 1759 (the filled purple circles denote water movements, the open circles denote sites with reportedly calm water, the blue triangles denote cracked ice, and the square denote landslides).

Along the coastline of Halland, Sweden, “the sea and waves made an unusual roar and rose in a similar way as on 1 November 1755” [21]. Another report from Halland told how difficult it was for two people in a boat to cope with the sudden strong waves [22]. An unusual roaring of the sea and sea waves was also reported from Marstrand, Sweden [23]. In Bergen, Norway, observers reported seeing turbulent water bubbling and swirling together with ground shaking, although the weather was calm. The reports were quite similar to the observations made in the same location after the Lisbon earthquake 4 years earlier [24]. The distance to Bergen, Norway, is approximately 385 km from the epicenter of the 1759 Kattegat earthquake; even if accounting for substantial location error, this effect occurred quite a distance from the source.

On the morning after the earthquake, people noted cracked ice in Vejlefjorden, as well as in Limfjorden close to the city of Aalborg, in Denmark [25]. According to one circular, ice vanished from the beach in Egebjerg, Zealand, on the night of the earthquake [19] (p. 181). Vicar J. Gothenius reported the following from the fortress of Karlsten in Marstrand, Sweden: “On the following day, I saw that the ice in all the ponds in the fortress had broken in many places, and with very irregular patterns. The same could be seen also

where the ice reached the bottom (of the pond)” [23]. The ice cracked on many lakes in western Sweden [26].

Minor cracks appeared between the bridges and the adjoining river banks in Halland [18,22]. The Kattegat earthquake also triggered one known landslide [18]. Large landslides occurred along the banks of the entire Göta River. The most significant of them occurred at Bondeström, in the municipality of Hjärtum, where observers said that the frozen river “sprang up and threw pieces of ice high in the air” [27]. This indicates that the ice (and underlying water) was displaced by the failing slope. The size of this landslide is estimated at 11 ha [28].

### 2.3. The Lurøy, Norway, Earthquake of 1819

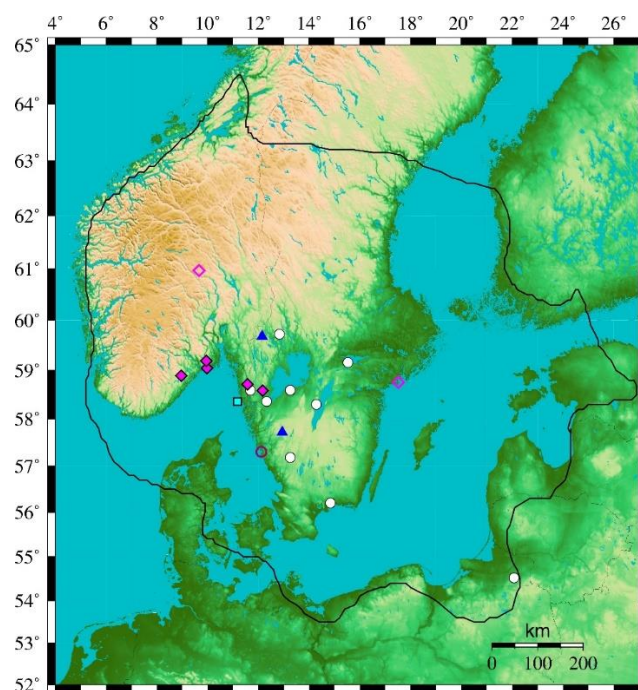
The epicenter of the earthquake of 31 August 1819 is estimated to have been near Lurøy, along the coast of Nordland, in Norway (Figure 1), with the magnitude recorded as a moment magnitude of  $M5.9 \pm 0.2$ , accounting for the uncertainty of the intensity assessment [29]. This reconfirms its ranking as the largest onshore or nearshore earthquake in the historical seismicity record of Fennoscandia. The earthquake was also felt in Stockholm, Sweden, and in Kola, Russia, at distances of approximately 840 and 890 km, respectively. The Lurøy earthquake occurred 60 years later than the Kattegat earthquake, but its location in the sparsely populated north meant that direct observations had to be disseminated via correspondence over long distances to larger documentation and population centers in the south. The Lurøy earthquake triggered remarkable EEEs (Table 1), including liquefaction and widespread rockfalls as well as strong water turbulence in the fjords, indicating fierce ground shaking [12,18]. Our starting point was the updated list of intensity data points, which incorporates previously unknown written sources [29].

### 2.4. The Oslofjord Earthquake of 1904

The earthquake of 23 October 1904 was the largest in the target region in the 1900s, with an estimated magnitude of  $M_S5.4$  [10], and the epicenter located at latitude  $58.69 \pm 0.10^\circ$  N and longitude  $10.86 \pm 0.18^\circ$  E in the proximity of the Swedish-Norwegian border [30]. Unsurpassed amounts of macroseismic data are available for this earthquake, including many sets of questionnaires collected in the affected countries and respective summaries published nationally or regionally (e.g., [31,32]). We also collected information on EEEs from contemporary newspapers.

Given the large number of lake basins of different sizes in the affected region, many localities reported turbulent waters (Figure 4 [33]). Large waves were felt in boats, causing trouble to sailors on, e.g., Lake Mängen and Lake Vänern, Sweden [34,35]. Steamboat passengers on Lake Vänern experienced the earthquake as a strong jolt, as if the boats had run aground [36]. Some reported seeing water moving strongly at Kinnevik, on the south-eastern part of Lake Vänern [37], with the water’s edge reportedly receding at the town of Hjo after having surged for some time [38]. The earthquake was also reported felt on larger ships (e.g., [39]). While such reports can be rather ambiguous regarding location, they still indicate that unusual, strong water movements occurred over a large area.

The water was reportedly calm near the island of Vendelsön along the coast of Halland, in Sweden [40], where no ground shaking was observed either and sailors did not notice anything unusual in the Straits of Kattegat and Skagerrak [36]. The earthquake’s effects were reported, however, far afield at a site on the southern coast of Sweden, where a dry well filled up with water after the earthquake [41], and the present-day Kaliningrad region, where a possible seiche wave was observed in a riverbed on the outskirts of the area of perceptibility [42].



**Figure 4.** Earthquake environmental effects related to the earthquake of 23 October 1904 (the white circles mark sites of water turbulence and the open circle a site of reportedly calm water, while the square marks land subsidence, the purple diamonds mark landslides and rockfalls, the open diamonds mark debatable landslides, the blue triangles mark ground moving in waves, and the solid line marks the area of perceptibility as outlined in 1913 [33]).

In Norway, the earthquake is known to have triggered several slope failures, including two rockfalls at Salsås near Larvik and Jordstøyp near Kvelde [43]. These events occurred at epicentral distances of 65 and 76 km, respectively. It was reported that more slides occurred in the same area. A soil or clay slide 18–20 feet in width was reported along a riverbank near the town of Gjerstad, approximately 112 km from the epicenter [44].

The earthquake also affected slopes in Sweden. One Swedish newspaper provided the following report: “the earthquake of 23 October caused a remarkable landslide on the high and beautiful mountain of Oxeklef in the vicinity of Bollungen in the municipality of Sundals-Ryr. Several larger boulders, almost resembling small hills, got loose and fell from the top of the mountain, which is at least 100 m high, down to the main road by the foot of the mountain, where a particularly large boulder landed, several cubic meters in size” [45]. Another rockfall occurred in the area of Bullaren in south-western Sweden [46]. The epicentral distances of these EEs were 76 and 40 km, respectively. A land subsidence was reported from Vaddö, on the western coast of Sweden, where a sandbank with length of 24 m and width of 16 m sank 10–14 m on the day of the earthquake. The sandbank was high enough for sailors to anchor at low tide and go ashore, but now it had vanished entirely [31,47]. The distance from the epicenter given above was approximately 25 km

### 3. Assessment of ESIs and Comparison to EMS-98 Intensities

Table 1 lists the ESIs and EMS-98 intensities assessed for the earthquakes of 1626, 1759, and 1819, while Table 2 lists them for the earthquake of 1904. We assessed the intensities based on the original written sources and collected information from localities in the proximity of the EEs described above to estimate the EMS-98 intensity.

A list of EMS-98 intensity data points was readily available for the 1819 Lurøy earthquake [29]. In the list, data from some localities were combined so as not to base the intensity only on environmental effects, in accordance with the EMS-98 guidelines [11]. Basically, making use of the ESI scale allows us to assign intensity ratings to a different

selection of places, but we focused on the localities as such for purposes of comparison. When using textual information, the general difficulty is that intensity assessment requires interpreting phrases that may lack detail, or for which only one classification factor is available, so a certain degree of uncertainty associated with the intensity remains. However, Tables 1 and 2 show that the overall agreement between ESIs and EMS-98 intensities is good in the range of IV–VIII.

Tables 1 and 2 also show the distances of the EEs from the respective epicenter. Landslides can occur far from the epicenter (e.g., [48,49]); this also means that the 1626 landslide (Section 2.1) cannot be used to infer the epicenter(s) of the respective, poorly documented earthquake(s). Here, the distances of landslides from the epicenter were less than 115 km, with the distances farthest away being associated with water movements.

**Table 1.** Environmental Seismic Intensities (ESIs) and European Macroseismic Scale (EMS-98) intensities for the earthquakes of 1626, 1759, and 1819 in Fennoscandia, northern Europe (the coordinates are given as longitude° E and latitude° N).

Country	Locality (Coordinates) Distance from the Epicenter	Excerpt or Summary of the Written Documentation [Reference no.]	ESI	EMS-98
<b>1626</b>				
Finland	Paltaniemi (27.664, 64.293) unknown	<i>The slopes of Lake Oulujärvi collapsed [17]. Largely observed, damage to a wooden church [17].</i>	IV	IV
<b>1759</b>				
Denmark	Frederiksværk (12.019, 55.969) 260 km	<i>Strongly felt in the water [19]. The tremor was so strong that, in some places, objects fell, doors swung open, not that strong in every place, but anyway with large movement and crashing sound [19].</i>	V	V
	Køge (12.18, 55.456) 320 km	<i>A fisherman observed unusual water movement [19]. Pieces of furniture moved rather strongly [19].</i>	IV	IV–V
Sweden	Frillesås (57.303, 12.182) 137 km	<i>Two persons in a boat had great difficulty in coping with the sudden strong waves [22]. The whole house shook, with doors and windows; the reporter felt dizzy in the head from the tremor [22].</i>	V	V
	Halland (12.744, 56.888) 194 km	<i>The sea and waves were seen to make an unusual roar and rose in a similar way as on 1 November 1755 [21]. Much stronger in Halland (than in Stockholm), strong shaking and jolts in houses, houses seemed to swing and rise, and be on the verge of collapse, doors swung open, loose pieces of furniture were shifted back and forth or fell over, but no particular damage was sustained at any place [21].</i>	V	V–VI
	Hjärtum (12.126, 58.145) 90 km	<i>Large landslips occurred along the banks of the entire Göta River. It was seen how the frozen river sprang up and threw pieces of ice high in the air [27]. The size of this landslide was given as 11 ha [28]. It was reported that the earthquake was very strong in the region (Bohuslän). Doors swung open, loose pieces of furniture moved back and forth, or fell over [21].</i>	VI	V–VI
	Marstrand (11.589, 57.886) 67 km	<i>Unusual roar of the sea and sea waves were reported [21]. The walls of the fortress have been inspected, but no cracks were found. In the bigger houses, both glasses and china clattered. In some places, glasses fell over. People were awakened [23].</i>	IV	IV–V
Norway	Bergen (5.33, 60.389) 385 km	<i>Turbulent water bubbling and swirling was seen together with ground shaking, although the weather was calm [24]. Houses shook [24].</i>	V	IV–V



Table 1. Cont.

Country	Locality (Coordinates) Distance from the Epicenter	Excerpt or Summary of the Written Documentation [Reference no.]	ESI	EMS-98
1819				
Norway	Bodö (Hundholm) (14.38, 67.28) 115 km (distance from Lurøy)	<i>Very severely felt. Some farms and several rocks were thrown down, the crest of one of which, overhanging the sea, was greatly shattered. The captain of a small vessel off Hundholm received so great a shock that he instantly let fall both his anchors, and prepared to warp off, thinking the ship had run aground [50].</i>	VI–VII	VII–VIII
	Hemnes (Hemnäs) (14.03, 66.05) 67 km	<i>The ground was trembling extremely strongly for 4 min, such that one thought, that the windows would fall in; the milk was splashing out of the troughs; in some places, the chimneys were damaged. Stor-Elven [river] was agitated as in the strongest storm. In several places, the water was seen both in the rivers and in Ransfjorden rising up as a fountain and accompanied by waves common for the strongest storm, though there was no wind in the air. During the earthquake, which was felt in the night before 1 September, a field of barrel seed sank into the deep at the farm Storstrand by Ransfjorden; later it fell piece for piece, such that 200 “alen” (a traditional Scandinavian unit of distance, about 60 cm) of the man’s farmed land has fallen away, thereby creating a drop (orig. Leerfald) of 30 “alen” in height, and it is not further than 4 “alen” from his dwelling, which is why the village was rapidly summoned and helped him move the houses of the farm. The first field that had sunken and transitioned to water came up again during a smaller ground shaking some days later. The beach front is filled with clay, creating a long, pointy headland [51]. At the farm Storstrand, in the Hemnæs district, this earthquake was devastating. The farmhouses were located on a large hill, and at the foot of this hill there was a non-negligible plain farmed with potatoes. During the earthquake, this plain dropped off together with the western part of the hill on which the houses stood. A very large 30–40 fathom (“favn,” 1 favn = 1.8288 m) drop was created in the mentioned hill and the plain below stood under water. The bank of the fjord, which was deep enough for the largest boats, was filled with gravel such that it was difficult to reach land. One neighbor had to, with the help of some people, move his farm [52].</i>	VII	VII–VIII
	Lurøy (12.86, 66.43)	<i>Not only the houses were shaking, but also the surrounding mountains, from which large rocks fell down, such that they were surrounded by much rock dust, as if they were surrounded by fog. Several springs, arising from the foot of the mountains, became unclear, as if they were mixed with milk, and their water was until on the third day undrinkable, even for the animals. The water had a smell of Sulphur, which was noticed at several places [53]. The houses were shaking. Rocks fell down from Lurøyfjellet in clouds of dust, and the water in the brooks became so cloudy that the farm animals would not drink it for 3 days. That the soil in several places is volcanic seems reasonable based on the frequent earthquakes occurring here, as well as it has been shown that it contains sulfur, which among others can be seen, at a brook at Lurøy farm, springing forth at the foot of Lurøeffjeldet, and with a lovely, crystal clear water; during the strong earthquake, which occurred in 1819, for several days it gave a milk-white water, had a strong sulfur taste, and was completely undrinkable [54]. In Lurøe Fjerdings and Trænørne, the earthquake has expressed itself strongly. From the large summits in Trænen, rocks fell, and out at sea and in the sounds rays of water were seen, and many of those who were at sea thought their boats would turn over [52].</i>	VII–VIII	VIII

Table 1. Cont.

Country	Locality (Coordinates) Distance from the Epicenter	Excerpt or Summary of the Written Documentation [Reference no.]	ESI	EMS-98
	Rana commune (Ranen) in Nordland county (14.34, 66.37) 66 km	<i>For a long time, the air had been full of rainy clouds, when finally, after 3 weeks of pouring rain, the sky cleared. The ground shook so violently that the windows shattered against the sun; in many places, the walls supporting the roofs fell down and the hollow roaring sound in the air lasted for 5 min, sounding terrible. In the mountain houses where the farmer had his milk standing on shelves under the roof, it splashed over. One saw on the completely calm Ransfiord rays of water standing high as a mast, and the water rose, even though the sea fell, over its highest flood banks. In some places, very fine sand was spraying up; it seems to have been taken from the intestines of the Earth, since one has been looking for it with no success. The mountains were shaking so strongly that the weathered rock masses on their tops and from their sides fell down with much banging and as a rain of dust against the sun's rays. The streams were cloudy from clay and soil. The ground shook so strongly that the people, who were out in the field, could not stand, since their knees would not carry them. This scene of horror lasted, as mentioned, for about 5 min, and when it stopped a violent hurricane came from the southeast, which did not last longer than 10 min [52].</i>	VII–VIII	VIII
	Saltdal (15.56, 66.92) 131 km	<i>The house was shaking so strongly, that the windows were rattling, and the floor seemed to have a wavelike motion, when walking across it. The weather was very warm, without clear sunshine, and quiet. It was the first more or less clear day in the last 3 weeks, during which time southwesterly wind and rain had ruled constantly. At the foot of the high mountain above the vicarage is a stream with two springs in the mountain itself. Its water turned completely white with clay, which could not be observed at its banks; this is usually not at all the case, not even during spring flooding. By further investigation, it was found that the water sprang out from the foot of the mountain, which seemed clearly to show how the shaking has worked in the lap of the Earth [55]. A strong rumble from the west-southwest, and the floor was as in a wavelike motion. The water in nearby streams became cloudy from clay, and some old stone walls fell down [54].</i>	VI	V–VI

**Table 2.** Environmental seismic intensities and intensities on the European Macroseismic Scale for the earthquake of 23 October 1904 in Fennoscandia, northern Europe (the coordinates of the localities are given as longitude° E and latitude° N).

Country	Locality (Coordinates) Distance from the Epicenter	Excerpt or Summary of the Written Documentation (Reference no.)	ESI	EMS-98
Sweden	Asarum (14.843, 56.199) 365 km	<i>A dry well was filled up with water after the earthquake [41]. The earthquake was felt differently in different parts of the town (Karlshamn). It was felt most strongly by people indoors in the southern and eastern parts of the town, where small objects shifted and flower-pots by the windows almost fell down in many places. Here and elsewhere, people outdoors felt weak shaking or nothing at all [56].</i>	IV	IV
	Bollungen (12.167, 58.590) 76 km	<i>Several larger boulders, almost resembling small hills, got loose and fell from the top of the mountain, which is at least 100 m high, down to the main road by the foot of the mountain, where a particularly large boulder landed, several cubic meters in size [45]. In near-by areas, very strong ground shaking was felt. In houses, pieces of furniture and objects shook so that much was broken; collapsed or partly damaged chimneystacks are seen here and there. Shop owners lost many items. Panic in the church [57].</i>	VI–VII	VI

Table 2. Cont.

Country	Locality (Coordinates) Distance from the Epicenter	Excerpt or Summary of the Written Documentation (Reference no.)	ESI	EMS-98
	Bullaren (11.567, 58.717) 40 km	<i>Steady regular rockfalls of boulders and stones have since (the main shock) been observed. Last night between Saturday and Sunday (29 and 30 October), a large landslide occurred, in which thousands of cubic meters of earth slid from the mountain into the river, blocking it over a distance of 40 to 50 m. The water is rising as this is being written, fast, and has already reached patches of rye field, where it causes damage [46]. Houses shook strongly, here and there a chimneystack collapsed, people run out of houses, many were frightened, houses sustained some nonstructural damage [58].</i>	VI	VI
	Flöghult (11.419, 58.985) 46 km	<i>Trees shook back and forth; in one pond water began to move strongly as if in a storm [31]. Chimneystacks collapsed, walls were cracked, mortar fell. The ground moved in waves so that many persons had difficulty in maintaining their balance [31].</i>	VII	VII
	Gothenburg (11.981, 57.675) 131 km	<i>In the sea, large waves appeared, lifting and pushing boats. Many observations of shaking from boats in the archipelago [31]. Felt everywhere in the town, chandeliers rattled, pendulum clocks stopped, lamps and other objects fell, pieces of furniture shifted, persons fell from the coach to the floor, people ran out of houses, frightened, damage to wallpaper and walls [59].</i>	VI	VI
	Gräbbestad (Grebbe stad) (11.254, 58.694) 23 km	<i>Small boats moved strongly up and down on strong incoming waves in the harbor; further out in the open sea strong jolts were felt in boats [31]. Many chimneystacks collapsed completely or partly; many walls cracked [31].</i>	V–VI	VI
	Hjo (14.288, 58.302) 204 km	<i>Water level in Lake Vättern seemed to recede after having rippled for a while. In a steamboat near the harbor pier, it was believed that the boat ran aground [38]. The ground shaking was felt differently in different parts of the town. Not everyone indoors noticed anything unusual, and some of those outdoors did not notice anything at all. Panic in the church and people ran out; a crack appeared in one of the church's walls. Here and there, pictures fell from the walls, smaller objects fell, mortar fell from the walls in some places, and some walls fell [38].</i>	V	V–VI
	Idala (12.324, 57.379) 169 km	<i>Trees shook violently [31]. Houses shook, so that windowpanes rattled, smaller objects fell, strong crashing of the walls [31].</i>	V	IV–V
	Kville (11.362, 58.569) 32 km	<i>The water in a nearby stream began to move strongly, and bubbles appeared on the surface [31]. Pieces of furniture shook and kind of jumped, pendulum clocks stopped, chimneystacks fell, and stones got loose from walls [31].</i>	IV–V	V
	Lidköping (13.15, 58.498) 134 km	<i>The ground shaking pushed the water of Kinneviken in a strong movement [37]. Parts of chimneys collapsed; panic in the church [37].</i>	V	VI
	Mangskog (12.823, 59.751) 162 km	<i>Large waves suddenly appeared in calm Lake Mängen. A flat-bottom rowboat was close to toppling over because of the waves [34]. Strong ground shaking, many minor cracks appeared in the church walls, panic in the church, the uppermost part of the church steeple, made of wood, shifted towards the east [34].</i>	VI	V–VI

Table 2. Cont.

Country	Locality (Coordinates) Distance from the Epicenter	Excerpt or Summary of the Written Documentation (Reference no.)	ESI	EMS-98
	Resön (11.174, 58.802) 22 km	<i>Water shook in springs so that it became mixed with clay. Strong water movement west of the island. Sailors felt such strong jolts that they thought they had run aground [31]. Strong ground shaking, hanging objects began to swing, objects fell from tables and shelves, chimneystacks fell and broke roof tiles, foundations of walls were cracked, stove pipes broke, etc. In some places, the pipes broke during the first shock, in others during the second one. Outdoors the tremor was so strong that people fell over [31].</i>	VI	VII
	Väddö, Tanum (Veddö) (11.267, 58.620) 25 km	<i>A sandbank with a length of 24 m and a width of 16 m sank and disappeared entirely [31,47]. The earthquake was felt very strongly [47].</i>	VII	VI–VII
	Vänersborg (12.324, 58.365) 92 km	<i>The jolt was felt strongly in boats on Lake Vänern. In one boat, located at a quarter of an hour's journey from the town, it was thought that the boat had hit a rock. The shaking sent ripples across the water [35]. Strong shaking, many windowpanes of shops were broken [31,35].</i>	VI	V

#### 4. Discussion

No fieldwork was carried out after the earthquakes of 1626, 1759, 1819, and 1904 in Fennoscandia. The seismologists' tool for collecting information remotely, the questionnaire, focused on how the earthquakes affected people and the built-up environment in 1904, but it did include a question on cracks in the ground and water movements. Unusual roaring of the sea was an item included on the 1759 circular. In the present investigation, EEEs have mainly been investigated using newspaper accounts not intended for research purposes. Newspaper data most likely captured the extreme rather than the average macroseismic effects [8], but the aim of such retrieval efforts is not to arrive at a statistical estimate. In particular, local newspapers can provide information on EEEs disregarded in the questionnaires.

One advantage of the ESI scale is that it does not specify building type, which can be complicated when evaluating the wooden houses in Fennoscandia. The scale also does not include a statistical estimate of the earthquake's effects on people, which is difficult to achieve in sparsely and irregularly populated regions, such as northern Fennoscandia. A challenge in using slope failures for intensity assignment is that the triggering of landslides is highly dependent on the level of water saturation in the slope prior to the earthquake. In that respect, intense precipitation or snow melting shortly before a large earthquake may strongly reduce the stability of a slope, thus making it much more prone to failure when ground shaking occurs. For example, the 1819 Lurøy earthquake occurred after 3 weeks of rainfall [29], which likely affected slope stability during the earthquake. This precipitation effect poses an extra uncertainty in the assignment of ESI, which is especially pronounced in areas of high precipitation, such as western Norway.

An illustrative example of the difficulty in correctly attributing the reason for slope failure comes from Nyköping, Sweden. Interested parties speculated as to whether the landslide at the end of October could have been triggered by the earthquake of 23 October 1904, which reportedly caused cracks in the ground there. It was then, however, noted that the cracks had formed prior to the earthquake [60].

EEEs are also affected by temperature: winter earthquakes may affect ice and snow. In addition to the 1759 Kattegat earthquake (Section 2.2), an example from the northern regions is the Siberian earthquake of 21 January 1725 (Julian calendar). The morning after the earthquake, the German naturalist and explorer D.G. Messerschmidt found that the ice covering the nearby Ingoda River had been cracked in many places [61]. Small-magnitude



earthquakes can also affect snow: “The tremors were strong enough to shake window curtains, split the stove in one house and cause loose snowballs to roll across the snow” [62]. The local magnitude of this earthquake in SW Finland at the beginning of 1900 may have been around  $M_L 3$ . Similarly to soils, the water content of ice and snow depends on meteorological conditions. Ice and snow are typically dismissed in intensity assessments, although snow avalanches are a widely recognized earthquake hazard (e.g., [63]).

Some of the uncovered reports suggest that the timeline of the EEEs was not limited to the main shock at approximately 11:30 a.m. local time on 23 October 1904. A local Swedish newspaper reporting on the earthquake that affected Bullaren, Sweden, wrote the following: “... From the Borgås Mountain steady, regular rockfalls of boulders and stones have since [the main shock] been observed. Last night between Saturday and Sunday [29 and 30 October], a large landslide occurred, in which thousands of cubic meters of earth slid from the mountain into the Grimmelandsälven River, blocking it for a distance of 40 to 50 m. The water is rising as this is being written, fast, and it has already reached patches of rye field, where it is causing damage” [46]. In addition, there are reports of a rock fall that occurred near Etnedal, Norway, approximately, 260 km from the earthquake’s epicenter, on 25 October 1904. This event may have been triggered by an aftershock [14,43].

Early publications recognized the risks posed to homes close to the riverbanks: “this occurrence [landslide of 1759] certainly is not the last of its kind, and thus, it is quite worrisome to see that many dwellings ( ... ) have been built almost right on the high, loose, and tilted riverbanks” [27]. Both the 1759 and 1904 earthquakes caused landslides and rockfalls in western Sweden (Sections 2.2 and 2.4). Even landslides with a relatively small surface area are potentially damaging. In the rockfalls caused by the 1904 earthquake, boulders fell onto a roadway [45] and into a river, causing flooding that reached rye crops [46].

Information on EEEs in the target region is scattered throughout a diverse array of documents. The sets of EEEs compiled as part of the present investigation are most probably incomplete, but even as such they demonstrate that EEEs are not unprecedented in the Fennoscandia region. We propose to include ESI values, when available, in the regional parametric earthquake catalogs and earthquake databases to increase the visibility of rare occurrences and highlight their risk potential. Columns of maximum macroseismic intensity and ESI give an instant overview of the societal and economic impact of past earthquakes.

## 5. Conclusions

The data sets compiled for the earthquakes of 1626, 1759, 1819, and 1904 in Fennoscandia, northern Europe, testify to such EEEs as rockfalls and turbulent waters. The overall agreement between ESIs and EMS-98 intensities is good, but many assigned intensities remain uncertain due to the character of the textual information and brevity of the documentation. Despite the difficulties with assessing intensity using historical data, EEEs should not be omitted from earthquake risk analyses. This investigation demonstrates that the ESI scale also has practical importance for regions with infrequent EEEs.

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